International Journal of Disaster Risk Reduction 31 (2018) 1295–1306

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Participatory early warning and monitoring systems: A Nordic framework for web-based flood risk management

Hans Jørgen Henriksen[a,*,1], Matthew J. Roberts[b], Peter van der Keur[a], Atte Harjanne[c], David Egilson[b], Leonardo Alfonso[d]

[a] Geological Survey of Denmark and Greenland, GEUS, Denmark
[b] Icelandic Meteorological Office, IMO, Iceland
[c] Finnish Meteorological Institute, FMI, Finland
[d] IHE-Delft, Institute for Water Education, The Netherlands

ARTICLE INFO

Keywords:
Early warning and monitoring
Public participation
Web-based access to data and model results
Risk communication
Flood risk management

ABSTRACT

This paper reviews recent hydrological risk assessment, communication and early warning systems and proposes a framework to reformulate the classic view of Early Warning and Monitoring Systems towards a participatory one. The new framework is developed for flood risks (from multiple flood hazards), using examples from selected Nordic and other European countries. The study shows a potential for public participation in all stages of the Disaster Risk Reduction (DRR) cycle, with enhanced risk communication and awareness. Web-based access to hydrological data and nationwide modelling results can support adaptive and integrated management and learning about the flood risks on catchment scale. This can help identify cost-efficient solutions with synergy to other policy goals. The study shows how social media and digitalisation initiatives in the Nordic countries can support web-based access to historical data, real-time forecasts, and climate projections. Furthermore, the web-based access to data and model results can provide a coherent and integrated platform for stakeholder interaction and co-production for planning and decision-making that integrate hazard and risk knowledge. This can increase societal resilience and flood risk assessment across community and sector boundaries with proper analysis of risk areas, trade-off in costs and benefits of different solutions, and optimisation of climate change adaptation at the catchment scale.

1. Introduction

In the policy-making arena, disaster risk communication is an important part of Disaster Risk Reduction (DRR). The Sendai framework [17] acknowledges the need for participation of citizens and non-professionals when dealing with multiple hazards. With the advent of the Information Age and new forms of social media, such participatory schemes and platforms, have become more interactive and dynamic. For qualitative research, the internet can be approached as a medium for communication, as a network of computers and as a context of social construction. Web-based access to data, model results to support participatory early warning and monitoring of flood risks on catchment scale have created new challenges for emergency response organisations and public entities responsible for flood risk communication. In Europe, the Joint Research Centre [2] has highlighted new emerging challenges related to risk communication, noting that key challenges are not so much about new tools and innovations, but rather about embedding social mechanisms in communication practice [2].

Web-based access to data and model simulations as part of early warning and monitoring systems (EWMS) and risk communication play a crucial role in both the survival and recovery of populations affected by disasters. Various tools can empower the local community to act in response to an early warning and support the adaptive capacity of local responding institutions [2]. Increasing public participation in disaster risk reduction and dealing with multiple flood hazards are promising, because these imply that focus is on risk, on how people understand and perceive the risk, how they spread information and how they are engaged in protective actions [2].

Early-warning and monitoring systems (EWMS) are defined as [8]: "*The set of capacities needed to generate and disseminate timely and meaningful information to enable individuals, communities and organisations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss*". While classical EWMS focus on risk knowledge and monitoring and warning services,

* Corresponding author.
E-mail address: hjh@geus.dk (H.J. Henriksen).
[1] Geological Survey of Denmark and Greenland, GEUS, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.

https://doi.org/10.1016/j.ijdrr.2018.01.038
Received 2 March 2017; Received in revised form 29 January 2018; Accepted 31 January 2018
Available online 02 February 2018
2212-4209/

participatory EWMS (pEWMS), according to Basher [1], make up the public part of EWMS. Basher's elements of pEWMS can be summarised as [1]: (i) risk knowledge; (ii) monitoring and warning services; (iii) dissemination and communication; and (iv) response capability. Transitioning EWMS towards pEWMS is about adding network-based, public participation to one or all of the four elements in order to provide more accurate warnings, more comprehensive damage evaluations and improved public risk perception and hazard awareness.

Traditionally, scientists and engineers have provided relevant parties in municipalities with reports or information on flood risks. Recently, however, web-based access to data and model simulations, as well as interactive tools have become available to support decision-making in flood risk management [2–7]. In this way, problems such as the consequences of measures pertaining to infrastructure or to the establishment of water retention can be analysed on a catchment level, and the results can be presented in intuitive ways, making it easier to understand for stakeholders with varying expertise and skills. Flexible solutions that can adapt to unknown, unexpected or changing conditions can be used.

This means that stakeholders and local communities can be more engaged in the risk knowledge production, and that authorities and stakeholders at different administrative levels, and across upstream and downstream community borders can interact in the risk knowledge communication.

Risk knowledge refers to the level of comprehension of each of the relevant risk components, including hazards and vulnerabilities. Examples of participatory elements include participatory mapping activities related to flooding [9,10], infrastructure vulnerability [11] and climate change impact and risk [12].

Flood risk communication covers a range of activities [18,20]. It can be activities that stimulate interests in environmental health issues related to flooding, activities that increase public knowledge about groundwater, storm-surge, consequences of subglacial volcanic eruptions, or influence the attitude and behaviour of people in emergency responses or crisis situations during flooding events. Additionally, flood risk communication can help the decision-making process or assist in conflict resolution [18]. Risk communication can be defined as [19] *"any purposeful exchange of information about health or environmental risks between interested parties"*. As highlighted by Kellens et al. [18], risk communication has evolved gradually from exclusive communication between experts into an inclusive engagement of risk managers and the public, instead of the previous expert-to-expert, linear communication, without public participation.

This paper aims to identify strengths, weaknesses, opportunities and threats of web-based access to data and model simulations and to add insight into participatory forms of early warnings and monitoring to reduce disaster risks. It also proposes a framework to reformulate the classic view of Early Warning and Monitoring Systems towards a participatory one.

The paper is structured as follows: Key concepts of participatory early warning and monitoring systems are described in Section 2. The methodology is described in Section 3. Section 4 summarises the Nordic survey for piloting results in Finland, Iceland and Denmark. Section 5 describes the knowledge elicitation results from European workshops. Section 6 discusses the findings and Section 7 presents the conclusions.

2. Key concepts of participatory early warning and monitoring systems (pEWMS)

Under the pEWMS, "top-down" and "bottom-up" processes can be bridged and better harmonised [30–34] to support stakeholder risk awareness and risk perception among local individuals and communities affected by flood. Adding "bottom-up" approaches [36] to classical EWMS allows stakeholders with access to local knowledge of environments and local networks to play a stronger role in decision-making and risk management. In addition, transparency in stakeholder participation, reflecting conflicting claims and views, may increase trust among stakeholders. Good risk communication holds the potential to build public trust, based on honest, clear, comprehensive and timely communication. It is important during all stages of risk management to collect systematic feedback from the community [37]. With the increased pressure on water resources and the challenges faced with the implementation of the existing regulatory framework, a growing lack of mutual trust between water stakeholders has been observed in recent years [38]. In order to elaborate on this ambiguity, we need to look into risk perception.

The notion of risk perception refers to the intuitive risk assessment of individuals and social groups with limited and uncertain information [21]. This assessment of risk varies between individuals due to various levels of information and uncertainty. Consequently, individuals in a community may perceive the risk of being flooded very differently, because they do not have the same information about the probability of hazardous floods or flood mitigation measures and their effectiveness. Perhaps they have a different historical and cultural background regarding the experience of living on a floodplain. Because of their specific perception of flood risk, individuals, social groups and public representatives, such as civil servants, may handle such issues differently.

A conflict of interest may also exist: experts responsible for flood protection may try to maximise their scientific information about flood hazards and flood risk in order to optimise the effectiveness of flood protection measures, whereas politicians may be more interested in attracting additional inhabitants or enterprises to a floodplain to strengthen regional economic development [22].

As underlined by Almoradie [30]: "*Stakeholder awareness and participation in disaster prevention and management are crucial and should cover all phases of any disaster event. Moreover, since stakeholders often have a better understanding of the real potential and limitations of their local environment, their involvement in planning and management are of crucial importance*". The recent advancements of the information, communication and mobile technologies and their applications (including SMS and apps) have demonstrated even more advantages for reaching and engaging the wider public and a broader group of stakeholders [35].

When dealing with various flooding events, early warnings need to provide forecasts for different time scales, from long-term climate projections and hydrological/hydraulic predictions, down to seasonal and monthly outlooks, 10-day forecasts, three-day forecasts, daily forecasts and all the way to hourly or immediate short-term warnings. Section 5 outlines the EWMS approach by the UK [23]. For pEWMS, a timely and meaningful (near) real-time-access to the state of the hydrological cycle (in terms of groundwater level and flow, soil moisture and river discharge), is useful for stakeholders and citizens to continuously update their information on the state of river flow, groundwater levels and visualised flooding risks [24,25]. Furthermore, this awareness and knowledge can be used to provide information about possible consequences and risks. Such pEWMS can, if properly enhanced with network-based participation, improve risk alertness and provide novel opportunities for risk management and disaster risk reduction [5]. As such, pEWMS could act as a potential hydroinformatics platform for knowledge-exchange among involved stakeholders, such as experts, citizens and the decision-makers [26], whereby the vital feedback pathways can be mobilised. Hydrologic/hydraulic model developers can benefit from more available real-time monitoring data for validating and updating their models, more efficient calibration and data assimilation, and decision-makers can incorporate value assessments by stakeholders.

Risk communication and flood risk management can support not only the building resilience and "bounce back" process, but also include how to "build back better" in recovery, rehabilitation and reconstruction of infrastructure and the build environment. Most notably, it does so in timely, actionable and inclusive ways. Participatory systems of risk communication and flood risk management are necessary to facilitate knowledge-sharing and public involvement in decision-making

[27–29].

As indicated in the examples above, various initiatives have explored the possibility of engaging stakeholders and the public through web-based access to data and modelling results for supporting DRR, adaptation to climate change and flood risk management on catchment scale. However, a clear framework that integrates the elements of flood risk knowledge, monitoring and warning services, dissemination and communication, and flood-response capabilities is not available.

There is a need for better integration of flood hazard and risk data e.g. hydrological terrain models with other hydrological data, infrastructure and land use data. Better access to data from rivers, preferably in (near) real-time. Better spatial data describing depth to shallow groundwater level, habitats, aquatic ecosystems, etc. to provide flood risk knowledge for local communities (municipalities), stakeholders and the general public resulting in cost-effective solutions locally in the catchment with the aim of reducing flood risks and increasing other values. Effects of future climate change should be included and visualised on maps and in time series (2050–2065, 2100) in order to evaluate cost-efficiency and valuation of solutions for a longer time perspective.

Different types of web-based information purposes (warning, monitoring, raising environmental awareness of citizens, etc.) may be subject to different behavioural and psychological mechanisms [37, pp.110–117]. Even though multi-purpose options for web-based information systems, as suggested here, are appealing in several respects, unifying the different goals of such a system may also be complicated. Dealing with new sources of information and understanding the way citizens provide information or become part of the risk communication are among the issues that deserve more attention.

This includes the development of sensors to be used by citizens [e.g. 16,13]. Recent research has demonstrated the usefulness of assimilating crowd-sourced data in hydrological models to improve flood hazard knowledge and forecasts [14,15]. Mazzoleni et al. [16,61] have also found that data collected by citizens, while being asynchronous and inaccurate, can still complement traditional monitoring networks composed of few static (traditional) sensors and improve the accuracy of flood forecasts. At the same time, current Information Technology (IT) products, such as social media, provide bigger data, different decision spaces, new uncertainties and unintended consequences. We need to be more critical about how data are collected, analysed and shared. The negative side of the Information Age includes potential privacy violations from big-data analytics used for surveillance. Here, multiple stakeholder involvement in impact assessment can be a way to detect privacy issues [2] at an early stage, and to evaluate any ethical issues that possibly hinder the display of photos etc. on web-pages open to the public.

3. Methodology

Our research approach includes an analysis of state-of-the-art pEWMS in the Nordic countries, combined with an analysis of findings from a number of European workshops.

We structure our findings according to Basher's four 'people centred early warning systems' elements [1,41], which include: risk knowledge, monitoring and warning services, dissemination and communication, and response capabilities (see Fig. 1).

As shown in Fig. 1, we have collected information about pEWMS systems dealing with flood hazards and risks in the Nordic countries. We have focused on river and groundwater flooding in Denmark, subglacial volcanic eruptions and river flooding in Iceland and flooding caused by severe weather in Finland. In the analysis of participatory elements (pEWMS) in these three Nordic countries, we have focused on how participatory monitoring and web-based access to data and model simulation results could improve flood risk analysis. Denmark's case involved the collection of new shallow groundwater level observations available from stakeholders and use of these data with web-based access to hydrological models. In Iceland, citizens participated in monitoring by uploading photos during flooding events, and in Finland, citizens' observations were included in mobile and online weather services.

Apart from Denmark, the Nordic countries are large and generally sparsely populated. While the culture and institutional settings are quite similar, differences in geographical and climatic conditions pose several challenges when making general conclusions about flood risk management under climate-change [39,40]. Therefore, the outcomes of the workshops are evaluated in terms of usability and applied value in the context of the Nordic countries.

Several European workshops were attended to increase the knowledge-base of pEWMS (Fig. 1), based on experience from the Nordic countries. A workshop in Amersfoort, The Netherlands, was hosted by the company HydroLogic which developed the HydroNET, a platform that connects decision-support applications with data services and models to support decision-making for sustainable water resource management (www.HydroNET.com) [42,43].

A second workshop held during the final EC-FP7 WeSenseIt project in the broader context of the Citizen Observatories for Water Management (COWM2016, Venice) provided useful insights into state-of-the-art tools for tapping into citizen observations. This gave examples of participatory monitoring and modelling that were useful for pursuing pEWMS in the Nordic countries, particularly in the fields of flood risk management, environmental monitoring and meeting the challenges of the European Water Framework Directive (2000/60/EC) and Flood Directive (2007/60/EC).

To follow up on COWM2016, a workshop was organised by Sheffield University to explore how physical and social sensors can be used by citizens to provide crowd-sourced hydrological data available in real-time on mobile platforms and software [16]. In addition, the workshop held discussions on how citizens' risk perception is relevant for citizen observations (see Section 2).

An additional workshop in Reykjavik elaborated on four themes: social framing of acceptable risk in implementing the Sendai framework of participation in hazard management; implementation of natural hazard management schemes in coastal flood risk management; applying risk assessment; and sharing responsibility and risk.

Finally, a workshop (EDUCEN, Dordrecht) dealt with culture in pEWMS and how to integrate this with risk perception and how to advance flood risk assessment approaches and consequence evaluations, to incorporate the impact of culture in the Nordic resilience model.

Public participation is not only fundamental to how pEWMS are designed and developed. For example users can engage in the design of web interfaces and methodology in order to gain a sense of ownership of early operational pEWMS. Furthermore, stakeholders can help implement the pEWMS in their local communities and share warnings in social networks.

Workshop attendance by the authors and other invited participants from the Nordic countries contributed to the aim of this study to learn from knowledge and experience in Europe and use this to advance pEWMS in our own organisations and in the Nordic countries.

4. Results of Nordic pEWMS review

To develop the knowledge base on pEWMS, we surveyed the development of prototype solutions in Finland, Denmark, Iceland, Sweden and Norway as illustrated in Fig. 1 and summarised below.

4.1. Denmark

In Denmark, the status of EWMS was explored at a workshop arranged as part of the end-user mapping of needs for EWMS based on the national hydrological model [24,25]. At the workshop, DHI presented more than 20 years of experience with EWMS [44] targeting flood risk management. The applications are varied, including flooding, operation

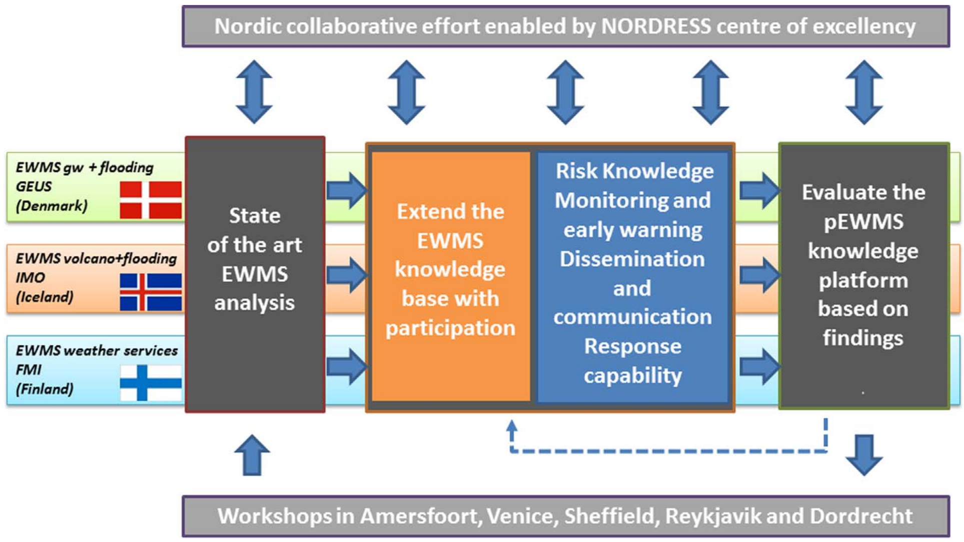

Fig. 1. Methodological approach. State of the art analysis in Denmark (GEUS), Iceland (IMO) and Finland (FMI) combined with exploratory workshops in European cities.

of reservoirs, sewage and rain water systems, irrigation, water quality, waste water treatment and water-supply issues. Recently, DHI implemented an EWMS for flooding on the Sava river (Slovenia and Croatia) that involves flood forecasting with a focus on emergency management and preparedness (e.g. equipment, relief work and sand bags).

The DHI Gudenaa experience in Denmark reveals several factors worth considering in the system design and application: a web-based river model with EWMS allowed for decision-support in relation to flooding, targeting different user levels: online warning for citizens and the public, off-line scenarios for experts and authorities (three municipalities) and river models for experts and consulting companies. Experience shows that key factors to consider are the quality of data, warning models fit for purpose, quality assured on-line data for assimilation, warning alarms and relevant, flexible information and a reasonable fit between user needs and delivered outputs by the EWMS.

To explore pEWMS options, GEUS designed a questionnaire on end-user needs of a hydrological real-time system for surface water and groundwater in Denmark and developed a prototype of a hydrological real-time system [24,25] using the MIKE customised platform. Forecast data for precipitation, global radiation and temperature were obtained from the Danish Meteorological Institute (DMI), based on the HIRLAM regional numerical weather model. A pilot catchment (Skjern Aa) was selected for developing a prototype demonstration based on the national hydrological model (DK model), see Fig. 2. A website was designed to display groundwater level, stream discharge and soil moisture in the root-zone in real-time and during the next 48 h (with an hourly forecasting interval). A one-day workshop was held with Danish end-users to discuss their needs. In ScienceNordic, a popular article was published on 5 January 2016 (and one in Danish in Videnskab.dk): *New model can help predict flooding two days in advance*. The ScienceNordic article [45] featured widely in the media because it was published at the same time as a major river and groundwater flooding event hit Denmark (and the northern part of the UK). These events failed to reach the intensity for a cloudburst (above 15 mm within 30 min) or heavy rain (above 24 mm within six hours). However, due to a long preceding period of almost continuous, low intensity rainfalls, the rain events caused extremely high groundwater levels and widespread inundation in the landscape and river flooding. Groundwater flooding is a relatively new type of flooding for municipalities, and it is not yet fully managed in municipality climate-change adaptation planning.

As part of Danish Digital Strategy 2016–2020, several initiatives were established in spring 2017, including one on common data in topography, climate and water, run by the Government, local governments (98 municipalities) and Danish regions. As part of this Danish Digital Strategy, a national pEWMS: HIP (Hydrological Information and Prognosis system) scenario has been designed with six elements: (i) Historical data and real-time observations; (ii) nationwide hydrological simulations and prognosis for the past, present and future; (iii) calculated indices (saturation degree, drought and flow indices) for various water management issues; (iv) EC Copernicus Emergency Management Services of flooded areas (historical and near-real-time data); (v) citizens' observations, to upload photos of flooding; and (vi) web-based interfaces for data and map-based results and time series (including anomalies).

In the next phase, an investigation of methodology for simulating shallow groundwater levels (groundwater flooding), water levels in rivers and flooding of land near rivers will be undertaken with two case-studies (Odense and Storaa). Development of the pEWMS HIP scenario is expected to start in January 2018.

4.2. Iceland

In Iceland, the Icelandic Meteorological Office (IMO) has developed an experimental pEWMS, including web-based solutions for the upload archival and visualisation of photographs taken by the public and other stakeholders such as the emergency services. Publicly uploaded photographs that assist with flood assessment are paramount to timely responses. GIS-based web-pages are used to display the latest incoming photographs for use in continuous round-the-clock monitoring at IMO. The system has been trialled for observations of flooding. Another example of pEWMS is crowdsourcing SO_2 pollution modelling and reporting which was implemented for the Holuhraun eruption 2014 using a cloud-based registration page from ESRI (Fig. 3).

The GIS-based web-page uses cloud-managed GIS services to provide an interactive map of Iceland, allowing users to pinpoint the location of a flood via three alternative methods. First, users can simply enter the beginning of an address into a search command, from where address details are retrieved. Second, mobile users may enable auto-location based on their phone or tablet's inbuilt GPS. This option yields accurate geographic location which is then displayed on an interactive map. A third option includes manually locating the photographer's location on an interactive map. The auto-locate option is especially useful for photographs taken on a smartphone with location-services enabled. Internet-based locations are less reliable and their accuracy varies depending on location and service provider.

Alongside geographic data, the notification page requires the name of the photographer, the date when the photograph was taken, the

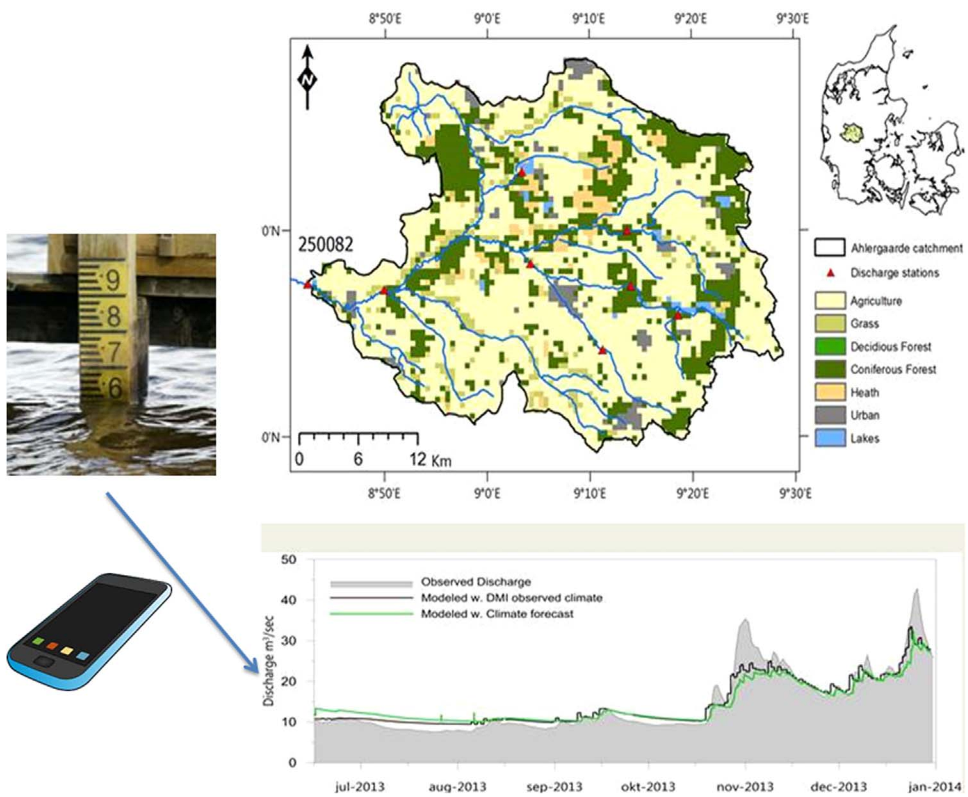

Fig. 2. Danish EWMS case for the pilot test catchment Skjern å. The approach includes real-time and forecast simulation with display of information on web sites and in-built verification of river change, which is a step towards full participatory involvement. To the left it is illustrated how the prototype can be further enhanced by participatory monitoring.

photograph itself and an optional comment. The design of the page allows it to be used in real-time or retrospectively; this greatly expands the potential for public notifications about flooding. Uploaded images are stored in a database at IMO where a separate map-based display at IMO indicating the location and public notifications can be created and viewed.

The page was put into full operational use in October 2016 during a period of prolonged, heavy rainfall which caused widespread flooding in the south and south-west of the country. The first version of the notification page was in Icelandic, accessible from IMO's home-page (see: https://vatnsflod.vedur.is/). The page was made available to foreign tourists via a short press-release on the English version of IMO's site; see: http://en.vedur.is/about-imo/news/reporting-floods-well-appreciated.

By receiving updates from potentially remote locations, this notification page helps to extend IMO's flood monitoring network to cover more possible flood locations. People involved in recreational activities, such as jeep tours or snow-scooter trips, cover large, often remote, areas and can upload photographs and observations of potentially hazardous conditions, such as the beginning of intense snow-melt. Thus, real-time flood monitoring can be expanded via public participation in the recognition and documentation of hydrological hazards.

4.3. Finland

In Finland, the Finnish Meteorological Institute (FMI) is responsible for weather-related early warnings for public and professional users. FMI also coordinates the national early warning system LUOVA [46] for all kinds of natural risks. Recently, FMI has taken steps towards pEMWS development as well. FMI's current online services reach hundreds of thousands of daily users, so the prospects for large-scale participation are good.

Firstly, FMI analysed user trends and user behaviour in online and mobile weather and climate services [47], and in April 2016, an online survey was conducted that collected 321 responses from FMI web and mobile application users. The behaviour analysis showed that mobile use of weather services differs from desktop use, as it is accessible to people throughout the day. The survey results indicated that there was potential in collecting a broad range of citizen observations, and that pEMWS were considered potentially helpful as long as the user interface is simple enough and users can tailor the warnings according to their needs.

Secondly, FMI piloted citizens' observations in a science education project aimed at high schools [48]. Within the project, over 200 high-school and primary school students from 12 schools around the country participated in collecting and analysing environmental observations. Although these observations were not integrated into operational warning products, the project showed that there is potential in mobilising targeted groups for environmental data gathering. This participatory work was also considered a success in terms of science communication and education.

Finally, in 2017 FMI launched a pilot project that integrated participatory citizen observation elements with the existing FMI mobile app. The system enables users to report their observations on rain, thunder, hail, floods, tornadoes and damage caused by winds. The observations include estimates of the intensity on a fixed scale and the possibility to enter free-form comments. Location and time are also included. During the first two months, 17,412 observations were recorded, of which 89% were observations of rain. Observations were collected from 7810 individual users, of which 167 made more than 10 observations.

The experience of FMI to date shows that it can collect large amounts of participatory observations relevant for flood risk management. These observations can be used in developing early warnings, although this integration is yet to be done systematically. They could also be helpful in retrospective verification of issued warnings. The social and psychological impacts of the participatory mode of action require further research to find out if the participatory component affects risk perception or preparatory behaviour.

4.4. Sweden

In Sweden, the national hydrological early warning and monitoring

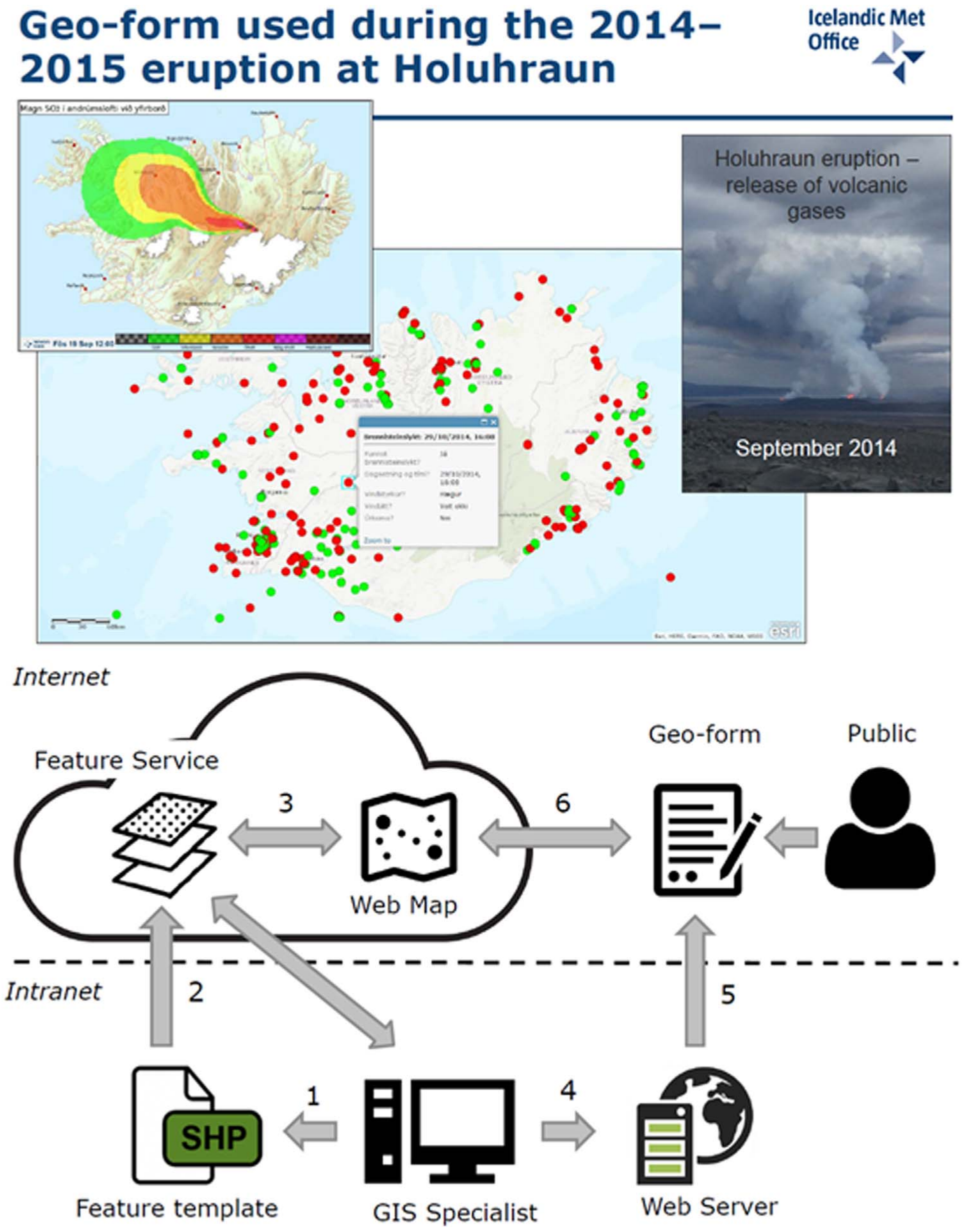

Fig. 3. Participatory flood risk early warning and monitoring prototype developed by IMO (pEWMS) first developed for SO2, subsequently adapted for upload of flooding photographs including upload of structured information.

infrastructure is based on a real-time hydrological model available from SMHI (Sweden's Meteorological and Hydrological Institute) with discharge information, including a prognosis for the next 10 days, and access to historical observation data. Effects of climate projections (2050 and 2100) are also available. A national distributed model is used (HYPE) with weather prognosis and hydrological forecasts for river discharge.

A photo gallery is the only participatory element incorporated in the Swedish web-based information system. The Swedish system is comprehensive in terms of incorporating access to historical data, model forecasts and climate change effects. However, participatory elements, groundwater and sea level data and infrastructure risk data are not incorporated.

4.5. Norway

Norway also has an established national early warning and monitoring system based on a national model to visualise hydrological conditions and forecast results (run by Norges Vassdrags- og Energidiroktorat), Met office and Kartverket. Hydrological cycle simulations are available on varying time-scales, including information on soil moisture for assessment of flood risks throughout the country. Historical data are also available to support valid model results. The system also covers the irrigation needs of the agricultural sector.

A photo gallery is the only participatory element incorporated in the Norwegian web-based access to hydrological data and model results.

5. European Workshop results

In Table 1, the results of the European workshops are summarised and structured according to risk knowledge, warning communication, response capability and dissemination and communication [1]. Many of the flood risk management issues discussed in Amersfoort considered the technical aspects of warning and risk communication, the technical capacity to monitor flooding hazards with various sensors and possible upgrading of warning services in order to improve preparedness. The

Table 1
Knowledge elicitation of findings from European workshops (Amersfoort, Venice, Sheffield, Reykjavik and Dordrecht).

pEWMS element Workshop	**Flood risk knowledge**	**Flood warning communication**	**Flood response capability**	**Dissemination and communication**
Amersfoort HydroNet	If citizens and communities are able to play a new role in the information chain, risk knowledge on flooding hazards and vulnerabilities of people and society is improved [6]	The technical capacity to monitor flooding hazards and to forecast flooding evolution and issuing warnings can be improved, whereby flooding monitoring and warning services can be upgraded [7–9]	Response capabilities in relation to flooding risks can be enhanced by better and more timely knowledge, improved plans and capacities for appropriate mitigation actions by authorities and those at risk.	Dissemination and communication in understandable ways of flood risks to those at risk can be improved, whereby preparedness can be increased.
Venice COWM2016 (Final WeSenseIt conference)	Citizen science, is a new approach for participation in risk knowledge provision, where citizens take an active role in the knowledge generation, supported by Apps, in collaboration with scientists	The focus is on participatory monitoring. There are only very few examples of Citizens' Observatories for groundwater. Most observatories focus on ecology in rivers and things which can be sensed and recognized with trained individuals.	There are a number of stakeholder incentives for participatory monitoring in river basins, not always neutral. Citizens' engagement can be particularly usefulness, especially in relation to flash floods where other warning systems may not be enough.	Dissemination and communication are often supported by ICT and/or social media. Citizens' engagement in crisis management can be a way of dealing with security and safety issues (malicious water contamination). A way of engaging citizens and communities for emergencies.
Sheffield WeSenseIt	The notion of social sensors contributes to mining / crowdsourcing local knowledge from citizens to authorities. Behavioural models can help understanding responses from citizens	Citizens provide information (social sensors) via e.g. social media using physical sensor on risk related hydrologic variables. Social- and physical sensors are integrated in web based platform / API to communicate warnings.	Response capability when using "two-way" communication (social and physical sensors) is enhanced as emergency management can tailor response activities in accordance with needs based on provided local and timely knowledge.	The integration of social and physical sensors via data sharing and modelling (scalable) platform is disseminated via e-collaboration apps / tools and external platforms (RSS, SMS, Twitter).
Reykjavik Acceptable risk workshop	Dam breaks is a good example of why risk knowledge is more important than hazard knowledge. Risk knowledge on evacuation plans is important in Dutch emergency planning. Dam breaks play a key role in the assessment.	Waning communication is a challenge for some hazard risks in remote areas (landslides and volcanic eruptions) in Iceland. Early warning systems for SO_2 in relation to volcanic eruptions can be enhanced by participatory monitoring (same for flooding).	Different response capability in different groups (local people < > 2 million. tourists per year). A kind of flexibility is required in order to allow farmers to feed their animals, during volcanic eruptions in Iceland. Modern transport systems (cruise ships and airplanes) are much more vulnerable, than propel airplanes and older ships.	Probability is not a meaningful way of communicating risks for most people. Better to provide scenarios and stress tests with what if simulations and use of system models for communicating possible consequences of coupled natural hazards. Different municipalities communicate different acceptable risks levels in coastal protection.
Dordrecht EDUCEN	Risk knowledge focus on cities, cultures, subcultures and catastrophes (earthquakes and flooding).	Communication needs to target social landscape and network "key players" in order to be efficient. Local knowledge important.	First responders key during natural disasters and early recovery phase. In reality cultures are very different from city to city (and subcultures)	Much focus on disabled citizens (old, young, gender issues), and the importance of cultural (and language) aspects of risk perception and risk communication.

participatory aspect is primarily about how citizens can take a new role and how apps and social media can be utilised to improve the response capability.

In the Netherlands, the HydroNET platform, developed for anticipatory water management, connects data services (on-line data) with model results, analysis tools and decision support applications and provides a facility for informed decisions. A scalable architecture and infrastructure for pEWMS was developed by the WeSenseIt project, illustrating the technical focus of WeSenseIt, investigating how to provide an improved database and data flow between agencies and stakeholders.

As examples of decision support applications, (Apps) the FloodWatch App can inform people accessible via mobile phones about risks of flooding and with alerts for selected locations and periods. The WeSenseIt project has shown that citizens and communities can play a new role in the information chain of water-related decisions and that there is potential to constantly monitor water resources to make sense of and react to sudden changes.

A similar example of the use of mobile phones was presented at the Amersfoort meeting by the Danish Red Cross, who presented their experience with VIEWWORLD, a mobile platform with structured upload forms for editing published data and download of data-sets related to aid projects in developing countries also exposed to flooding and erosion. The need for maintenance of built infrastructure can be documented via photographs from mobile phones to Danish Red Cross in order to document needs for maintenance and provide early warning communication relevant for an aid agency working in developing countries. The Danish Emergency Management Agency, DEMA, presented a recently released App providing early warnings to the public about traffic accidents, weather conditions and risks due to natural hazards. The new App released just after the Amersfoort meeting also links to social media, including Twitter. Options for enhancement into a “two-way” pEWMS were also discussed. The issue of warning thresholds is important, in order not to overwhelm users with warnings.

The *COWM2016* conference in Venice focused on the potential for Citizen Science in the European water innovation landscape, and specifically the fields of flood risk management, environmental monitoring and meeting the challenges of the European Water Framework Directive (2000/60/EC) and the Flood Directive (2007/60/EC). Participation provided useful insights in state-of-the-art knowledge regarding Citizens' Observatories (see Table 1). Citizens' Observatories related to groundwater focus are rare or non-existing and how to cover this gap with adequate pEWMS is an open question. Citizens' Observatories do not in general use the observers for very simple observations like water level, they tend to focus more on pattern recognition and tasks where the human “sense machine” can be better utilised for identifying or recognising different communities (plants or animals).

The Sheffield meeting focused on discussing the results of WeSenseIt regarding flood risk management and social sensors for crowdsourcing local knowledge and citizens' response to novel tools developed in WeSenseIt. Techniques for using physical sensors and social media in warning communication were discussed. Synergies of “two-way” communication and response capability were discussed, and technologies for integration of social and physical sensors via data sharing and modelling analysed.

The acceptable risk workshop in Reykjavik addressed different aspects of acceptable risk viewed from expert-to-expert and participatory/cultural viewpoints. An example of a national flooding early warning system was presented by UK EPA for flood risk communication for the UK. Hazard warnings with different time perspectives: predictions more than 3 months ahead, 2–3 months checks for flood risk, one month sensitivity to rainfall, 6–10 days ahead with hydrometeorologial guidance provide improved risk communication to citizens when flooding risks are high [23]. The UK EWMS is mainly a national top-down driven hydrological early warning system for issuing hazard flood warnings. Risk knowledge is mainly provided by researchers and modellers, while the role of communities and feedbacks is not really covered by the EWMS. However, risk communication and emergency messages are disseminated and communicated on web-interface in meaningful ways.

Another flood risk early warning example relating to dam break risk was presented by Norway Geotechnical Institute [49], namely the Usoi Dam in Pakistan (the largest landslide dam in the world), where establishment of an early warning system is evaluated to be capable of reducing the flooding risk for the exposed downstream population from severe risk to marginally tolerable risk. The problem with this large landslide-created reservoir is that in case of increasing water level, the dam can be eroded with severe damage to downstream cities along the main river. For such risk assessment, probabilities do not provide any meaningful information. Instead, stress tests are recommended because the weakness of the system is identified based on model simulations rather than probabilities, and possible win-win solutions are identified and assessed in collaboration with stakeholders.

The EDUCEN final conference in Dordrecht on 29–31 March 2017 focused on cities, cultures and catastrophes and included insight into the city's water safety strategy and multi-layer strategy attempts to deal efficiently with flood protection and flood risk management. A central theme of the conference was the improvement of impact assessments for society. When we know the impact, we can better advise our citizens and improve analysis accordingly. A key question that emerged was how to reach and engage the whole group, e.g. people under 50, by creative means.

One of the important outputs from the EDUCEN project is the online EDUCEN HANDBOOK building on learning experience from the seven EDUCEN case studies. Three of the case studies focused on flooding, others on earthquakes. Through these cases, EDUCEN has shown that it is relevant to focus on social networks rather than individuals when developing APPs. Also, practical exercises and serious games can be ‘empathy machines’ and are useful for emergency training exercises for flooding. Other examples include the flood resilience game (developed elsewhere).

It is important to approach citizens in wise, smart ways, and linkages (relationships) between professional emergency managers, local leaders and volunteers may be of benefit in DRR and flood risk management. “Flood cultures” (how communities approach flooding, authorities etc.) can vary widely by country and city and have to be approached accordingly in order to be effective. Some communities have a high level of institutional trust, whereas for others, institutional trust is lower, and therefore voluntary organisations in some cities and communities should be targeted.

Based on the experiments of piloting pEWMS in Denmark, Iceland and Finland and the findings from the five European workshops, a Nordic framework and knowledge base for pEWMS for natural hazards has been developed. The new framework, which is an extension of the framework proposed by Basher [1], comprises the following four functional components:

(i) *participatory flood risk knowledge assessment* of socio-technical system-dynamics (flood hazard knowledge, research/education, institutional commitment and mechanisms, disaster risk reduction measures/mitigation and preparedness)
(ii) *participatory flood risk early warning and monitoring system* providing historical monitoring data, system-dynamics models and effects of climate change with probabilistic predictions and what if stress tests flood risk consequences
(iii) *web based access to flood risk data and model simulations* that can properly handle “top-down” and “bottom-up” communication lines and feedbacks between system components, with a community-centred dissemination and communication, constantly informing all actors involved in the DRR cycle about preparedness and response actions
(iv) *multiple flood hazard aware response behaviours* performance

Table 2
Conceptual framework for a Nordic pEWMS for flood risk management (Basher 2006; Jonoski 2002; Almoraide 2014; Mysiak et al. 2010).

Functional components of pEWMS	Definition of functionality	Components for supporting participatory early warning and monitoring of flood risks (pEWMS)
Participatory risk knowledge assessment	Socio-technical research, education, preparedness planning focusing on multiple-risk knowledge. Leadership and institutional commitment (interdisciplinary).	Involvement of all actors and stakeholders
Flood risk knowledge		Integrated and multi-hazard pEWMS Systematically focus on risk and vulnerability Provide multi-functional DRR and CAA adaptation measures Explore social-technical aspects Deal with all types all aspects of uncertainty (multiple knowledge frames/ ways of knowing, multiple languages/sub-culture; epistemic and stochastic uncertainty/variability) Science based approaches to DRR/CCA/adaptive management
Participatory early warning and monitoring system	National pEWMS which gathers, organises, provides and distributes relevant scientific knowledge, e.g. models, time series and spatial data, measures and strategies, open access to data, in accessible formats for downstream services.	Open access to meteorological climate observations and hydrological predictions (historical, real-time and early warnings) – models and observations
Flood risk early warning and monitoring	End user-defined web design and functionality.	Web-based interface to results of national hydrological model: simulation of hydrological cycle and all flooding types) Access to on-line observations of water level in rivers, groundwater and soil Near real-time satellite data based on monitoring of areal flooding from Copernicus services Development of real-time assimilation methodology (river water and groundwater levels and satellite data for accurate warnings) Access to climate scenarios for 2050 and 2100 for climate change adaptation planning and long-term early warning Opportunities for incorporating user defined mitigation measures and citizens' observations by photos or observations or interpretations via smartphones
Web-based access to flood risk data and model simulations	Integrate and provide feedbacks between different components and allow formulating judgements about the proposed plans or interventions. Combines the participatory early warning and monitoring with risk knowledge and the beliefs and attitudes of the users/participants in decision-making process	Citizen and stakeholder observations (water level, flow etc.) can be used in pEWMS
Dissemination and communication		Decision support system (GIS based risk assessment, Decision tree, Multi-criteria etc.) is available "in cloud" for downstream services Boundary fluxes to comprehensive or local community models are available for municipalities and regions Pre-simulated maps of hazards for given observed or modelled system variable are available Use of coupled models (e.g. deformation model in the case of flood modelling) for calculation of increase in terrain level is included in services Beliefs, attitudes and preferences by stakeholders are collected and made available/transparent Valuation criteria and decision support system (scenarios, insurance/ financing etc.) is available
Multiple hazard aware response capability	This component has to aggregate (community centred) the judgements and evaluations performed by the participants in the system, present what is known as 'social landscape', (explore the options for mutual gains when exposed to single or multiple hazards	Hazard, vulnerability and consequence (exposure) learning process is running
Flood response capability		A common risk understanding has been established A shared vision on acceptable risks has been developed and agreed upon More stakeholders have been included in scenario development An action plan for reducing residual risks has been prepared and implemented Action plan has been discussed with policy makers from different sectors Risk reduction coalitions have been established. Capacity/stress test pilot adaptation projects/participatory integrated assessments have been started Participatory evaluation / valuation at system/sub-system level (multifunctionality) is in operation New business models, policy uptake, integrate & mainstreaming in WFD/ Flood directive etc. have been developed

indicators and benchmarks and economic and socio-economical value assessments of risk consequences and warning system effectiveness

The Nordic pEWMS framework is briefly illustrated in Table 2 and will be further discussed in the section below.

As illustrated in Table 2, participatory flood risk knowledge assessment requires constant adaptive, integrated and inclusive risk management (or governance) organised as learning cycles with the engagement of a broad group of stakeholders. Web-based access to data and national model results allows for continuous exchange of information between different players taking part in the water

management, DRR and CCA cycle.

6. Discussion

The people-centred EWMS elements in [1], namely risk knowledge, monitoring and warning services, dissemination and communication and response capabilities have been adapted and extended to include the active participation component in EWMS. The resulting adapted elements are, correspondingly, participatory risk knowledge, participatory Early Warning and Monitoring System, web-based access to flood risk data and model simulations as well as multiple hazard aware response capabilities for flood risk management (Table 2).

6.1. Participatory flood risk knowledge assessment

The increasing awareness of both scientific and policy uncertainties in flood risk and groundwater management and the potential of pEWMS has led to a re-assessment of the way natural systems are managed [50], encouraging a more adaptive process [51]. Adaptive management copes with uncertainty by increasing resilience [52] and creating flexible nature and engineering based solutions that are able to adapt to unknown, unexpected or changing conditions.

Adaptive water resource management has provided the idea of introducing learning cycles [51] in order to adapt water management and support robust decision-making with focus on reframing (double loop learning), or with the purpose of transforming the context (triple loop learning). A timely fashion implementation of the new pEWMS paradigm is needed for allowing such robust decision-making, efficient risk management and broad focus on resilience and vulnerability instead of a narrow focus on hazard mapping. The generation of knowledge about vulnerabilities and risks has to be more timely, efficient and participatory in order to address the new challenges for emergency and risk managers and to support stress testing.

This means that for properly managing acceptable and residual risks related to more unpredictable dynamics of water, more advanced pEWMS are needed which allow better integration of technical task and social-relational activities. Possibilities for analysing alternative scenarios and addressing what-if questions seem to be very important [50]. Wehn et al. [53,54] show that different authorities have differing perceptions of citizen participation in flood risk management in terms of their roles and influence. Our results also indicate that these perceptions can support and enhance the different stages of the disaster cycle (prevention, preparedness, response and recovery).

6.2. Participatory flood risk early warning and monitoring system

In combination with real-time information and network based participatory processes, the stakeholders' and citizens' understanding of the real potential, their preferences, beliefs, attitudes and valuation of various ecosystem services and the limitations of adaptation measures and risk assessment of their local environments can be incorporated in warning and monitoring.

As part of the WeSenseIt project, [55] argue that citizens' observatories in flood management provide a unique way of engaging the public in the decision-making processes associated with flooding. Citizens can play a role in the collection of qualitative and quantitative data in influencing the actions of the local authority and provide peer-to-peer information for their fellow citizens. For the local authority, the benefit is a significant increase in the amount of real-time information and improved situation awareness. For the citizen, the benefit is the availability of a much richer, up-to-date status of their locality, capturing not only environmental data but also information and discussion from their neighbours and fellow citizens. Therefore, pEWMS tailored to local communities and management needs are desirable, and possibilities for exchange of data and knowledge between national and local EWMS/pEWMS should be properly considered.

Due to the relatively high costs for society related to flooding, some non-Nordic countries (e.g. UK and USA) have initiated EWMS of water levels in rivers, with warning messages for low, normal and high flooding risk. This way, citizens and authorities are informed about the current state of important hydrology variables on web map services and will be better prepared for emergency management activities. In the US, this has been further advanced to visualisations on maps showing the extent of flooded areas along rivers. This is obtained by the use of digital terrain models and hydrological and hydraulic modelling of water levels in real-time [56]. It is also possible for users to receive forecasts of expected flooding risks issued every 6th hour in cases where critical water level has been exceeded. This system has been developed in cooperation between National Weather Service and U.S. Geological Survey. In Nordic countries, e.g. Sweden, such nationwide systems are available with web-interface for surface water (http://vattenwebb.smhi.se/).

Real-time information has been used operationally in hydrology in connection with flood forecasting [57,58] but so far, the use of this information for groundwater management is rare. Groundwater management and dealing with the associated complexity influenced by groundwater abstraction, the impacts on freshwater and terrestrial ecosystems and groundwater flooding, require an integrated hydrological model as described for the national EWMS that includes a feedback mechanism between surface water and groundwater.

The lack of tradition for real-time groundwater modelling implies that there are no readily available tools dedicated to real-time groundwater oriented data acquisition and hydrological modelling. Running a national EWMS in real-time will inherit all the challenges similar to running real-time surface water or precipitation runoff models, such as data management and display of results. Web-based interactive tools have recently become available to support decision-making in flood risk management [29] but have not yet been developed for real-time groundwater management.

6.3. Web-based access to flood risk data and model simulations

At the stakeholders' end, when presenting in local pEWMS in a "two-way" information system, a web-based (or App-based) graphic interface provides information which is supported by complex physically based models (the national EWMS fact engine or by local complex hydrological models of flooding risks like MIKE SHE/MIKE 11, Mike Urban, Mike Flood, Mike 21 etc.) presented in intuitive manners that can be understood by stakeholders with varying expertise and skills.

In many Northern European countries, there is not a very supportive culture among citizens for taking photos and uploading to web portals, since there is a general expectation that this is something that authorities and trained scientists should do, especially if there is a physical danger involved in collecting such data. The transferability of citizens' observations to a Nordic context is therefore not straight forward. In urban areas, there is also potential for pEWMS in relation to numerous climate change adaptation projects, planned and implemented especially in Copenhagen and other Nordic cities [40,60]. Here, the need for monitoring groundwater levels and possibilities for uploading data and photos of flooding events (flooding of cellars, green areas etc.) would be useful and for informing local authorities about the need for mitigating actions and solutions. Arguments against upload of geographically detailed data are grounded in the issue of privacy, unless such data are aggregated to subareas (for anonymity).

Wehn and Evers [54] analysed the social innovation potential of citizens' observations to increase participation in local flood risk management. They found that roles that authorities conceive for citizens and roles that citizens in practice assign to themselves can diverge. They also found that citizens' observations do not automatically imply that citizens have a higher level of participation in flood risk management, nor that communication between stakeholders improves.

Mazzoleni et al. [16] argue that in spite of this, data collected by

citizens, characterised by being asynchronous and inaccurate, can still complement traditional networks formed by few accurate, static sensors and improve the accuracy of flood forecasts. This was demonstrated for four different catchments varying from 135 km^2 to 822 km^2 in Luxemburg, UK and Italy. Catchments in the Nordic countries can be much larger and are also typically more sparsely populated and government networks less dense, both of which can have implications for the applicability and added value of crowdsourced data in hydrological modelling of flooding.

Findings from European workshops show somewhat mixed results regarding the value of Citizen Observatories when dealing with flooding and complex systems like groundwater. There are many Citizen Observatories in other areas which seem to work well (observations of rare species, plants, animals etc.) but for flooding and groundwater management, the results are not very clear, and good examples for dealing with Citizen Observatories for groundwater are rare or non-existing. However, upload of photos of water level during hazard events is a possible option, especially in remote areas (e.g. parts of Iceland, Sweden, Norway and Finland) with difficult access by authorities. This may be a good option for collecting additional data where present knowledge is limited in cases of flooding events.

6.4. Multiple flood hazard-aware response behaviours

Multiple flood hazards and risks require a targeted preparedness and response that address the multiple, coupled or sometimes cascading hazards with different strategies depending on time frame and scale. Some floods, like flash floods or cloudbursts, can evolve within minutes or very few hours, which means that it is not possible to activate flood defences or to provide reliable early warnings in time and space. Other flood types, like flooding from rivers and storm surges, can be forecasted with greater accuracy and reliability for the next hours and days. In these cases, flood defences and preparation can be arranged by emergency management, and warnings can be communicated by multiple media channels. Yet other types of flooding, like groundwater flooding, can have a time scale of several days to weeks and months. In such cases, other types of emergency management plans can be activated, like installing pumps or changing groundwater abstractions and managing crops [2].

Finally, web-based access to data and model simulations requires more research and testing for the assessment of trade offs and integration of consequences for different sectors and stakeholders when dealing with multiple hazards. Incorporating socioeconomics characteristics, engaging affected parties, champions and constantly adaptive governance in EWMS can develop institutional and mutual trust [59]. Web-based access to data and model simulations can pave the way for development of targeted downstream services (Apps), focusing on different goals of such services, e.g. climate change adaptation, emergency management and water management. Thus, pEWMS web-based services offer an opportunity to serve multi-purpose options and unify different goals.

Challenges in a pEWMS-based comprehensive flood risk governance are: (i) to balance precautious responses and pro-active prevention, (ii) to apply new governance strategies which can combine effectiveness, efficiency, resilience and fairness in order to achieve legitimate and public support, (iii) to ensure involvement of stakeholders, agencies, local communities and affected individuals and groups, and finally (iv) to initiate both capacity building and convincing narratives that help people understand their opportunities and risks and prepare them for their role in the new information age [37].

7. Conclusion

A review of recent initiatives in Europe and the Nordic countries regarding early warning and monitoring systems in relation to flood risk management and implementation of the Sendai framework, suggests that there is great potential for adding more participatory approaches to EWMS, including citizens' observations. It is argued that an added value of pEWMS is increased awareness about risks related to natural hazards and improved preparedness and response.

The framework proposed by Basher (2006) based on four interacting elements of EWMS (ISDR, 2005) and introducing the human factor ('people-centred') has been extended to participatory EWMS (pEWMS) and illustrated for the Nordic context. Hence, the four elements of EWMS have been adapted to: (i) participatory flood risk knowledge assessment, (ii) participatory flood risk early warning and monitoring systems, (iii) web-based access to data and model simulations and (iv) multiple flood hazard aware response capability (Table 2).

The generation of knowledge about vulnerabilities and risks has to be more timely, efficient and participatory. Participatory national early warning and monitoring systems should be tailored to the risk management needs of local communities, e.g. facilitating adaptive management of flooding risks to support social learning and robust decision-making. In addition, it is safe to conclude that encouraging citizen collection of timely and local knowledge can enhance disaster risk reduction at the municipality and regional level.

We argue that national pEWMS are valuable for real-time and forecasting applications with both short, medium and long lead times: short-term hazards, including flash floods and cloudbursts, with early warnings ranging from a few minutes to hours; medium-term hazards, including river floods and storm surges, allow forecasts ranging from hours to a couple of days before the hazards strike. Longer term types of natural hazards include groundwater flooding with warnings days to weeks before the slow onset hazard fully evolve.

The difference in short-, medium- and long-term hazard response time complicates transferability of Citizens' Observatories, especially when dealing with intermediate to slow onset hazards like storm surges, river flooding and groundwater flooding. In more remote areas, like many parts of the Nordic countries, the potential for participatory EWMS, however, is high as argued in this paper. Especially for flooding events, additional information sources from pEWMS are very useful, both during the response and recovery phase of hazard events.

Acknowledgement

This paper is a deliverable of the Nordic Centre of Excellence for Resilience and Societal Security – NORDRESS, funded by the Nordic Societal Security Programme (2015–2019). Participation in workshops in the Netherlands, Italy, the UK, and Iceland was funded by NORDRESS mobility grants. For further details about the NORDRESS project, see: http://nordress.hi.is/. Editorial guidance from David Alexander and comments from guest editor and three reviewers, and fresh eye opinions by Prof. Jens Christian Refsgaard, GEUS, and Aldis Elfarsdottir, IMO, helped to improve the focus of this article.

References

[1] R. Basher, Global early warning systems for natural hazards: systematic and people –centred, Philos. Trans. R. Soc. A. 364 (2006) 2167–2182, http://dx.doi.org/10.1098/rsta.2006.1819.
[2] K. Poljanšek, M. Marín Ferrer, T. De Groeve, I. Clark, Science for Disaster Risk Management 2017: Knowing Better and Losing Less, Publications Office of the European Union, Luxembourg, 2017, http://dx.doi.org/10.2788/842809.
[3] M.B. Abbott, Hydroinformatics: Information Technology and the Aquatic Environment, Avebury Technical, Aldershot, UK, 1991, p. 145.
[4] M.B. Abbott, Introducing hydroinformatics, J. Hydroinformatics 1 (2001) 3–19.
[5] I. Popescu, Mathematical Modeling in Support of Water Management – a Hydroinformatics Approach – Contributions of the Candidate to Hydroinformatics, UNESCO-IHE, 2014, p. 93 (Habilitation thesis).
[6] I. Popescu, Computational Hydraulics: numerical Methods and Modelling (ISBN: 9781780400440), IWA Publishing, London, UK, 2014, p. 160.
[7] A. Jonoski, Hydroinformatics as Sociotechnology: promoting Individual Stakeholder participation by Using Network Distributed Decision Support Systems, Sweets & Zeitlinger B.V., Lisse, The Netherlands, 2002.
[8] UNISDR. Terminology on Disaster Risk Reduction. 〈http://www.unisdr.org/files/

7817_UNISDRTerminologyEnglish.pdf〉.
[9] Phong Tran, et al., GIS and local knowledge in disaster management: a case study of flood risk mapping in Viet Nam, Disasters 33 (1) (2009) 152–169.
[10] Jake Cadag, D. Rom, J.C. Gaillard, Integrating knowledge and actions in disaster risk reduction: the contribution of participatory mapping, Area 44 (1) (2012) 100–109.
[11] S.M. Labib, MdShahadathHossain Patwary, Ishrat Islam, "Participatory Vulnerability Mapping: A case study on community based disaster management in (ward 13) Dhaka city, Bangladesh.", 2017.
[12] S.K. Maharjan, et al., Participatory vulnerability assessment of climate vulnerabilities and impacts in Madi Valley of Chitwan district, Nepal, Cogent Food Agric. 3 (1) (2017) 1310078.
[13] Ehsan Abiei, et al., Rainfall estimation using moving cars as rain gauges-laboratory experiments, Hydrol. Earth Syst. Sci. 17 (2017) 4701–4712.
[14] M. Mazzoleni, L. Alfonso, J. Chacon-Hurtado, D. Solomatine, Assimilating uncertain, dynamic and intermittent streamflow observations in hydrological models, Adv. Water Resour. 83 (2015) 323–339, http://dx.doi.org/10.1016/j.advwatres.2015.07.004.
[15] M. Mazzoleni, L. Alfonso, D. Solomatine, Influence of spatial distribution of sensors and observation accuracy on the assimilation of distributed streamflow data in hydrological modelling, Hydrol. Sci. J. (2016) 1–19, http://dx.doi.org/10.1080/02626667.2016.1247211.
[16] M. Mazzoleni, M. Verlaan, L. Alfonso, M. Monego, D. Norbiato, M. Ferri, D.P. Solomatine, Can assimilation of crowdsourced data in hydrological modelling improve flood prediction? Hydrol. Earth Syst. Sci. 21 (2017) 839–861, http://dx.doi.org/10.5194/hess-21-839-2017.
[17] UNISDR. Sendai framework for disaster risk reduction 2015–2030. 〈http://www.unisdr.org/we/inform/publications/43291〉. 32p.
[18] W. Kellens, T. Terpstra, P. De Maeyer, Perception and communication of flood risks: a systematic review of empirical research, Risk Anal. 33 (1) (2012) 24–49.
[19] V.T. Corvello, The perception of technological risks: a literature review, Technol. Forecast. Social. Change 23 (1983) 285–297.
[20] T. Terpstra, M.K. Lindell, J.M. Gutteling, Does communicating (flood) risk affect (flood) risk perceptions? Results of a quasi-experimental study, Risk Anal. 29 (2009) 1141–1155.
[21] Slovic 87. Perception of risk. Science 236: 280-285, 1987.
[22] F. Messner, V. Meyer, Flood damage, vulnerability and risk perception – challenges for flood damage research, Flood Risk Manag.: Hazards, Vulnerability Mitig. Meas. (2005) 149–167.
[23] M. Franklin Flood risk mapping and forecasting in England. Environment Agency, England. in: Proceedings of the NORDRESS Workshop on Risk Assessment and Acceptable risk. 〈http://nordress.hi.is/wp-content/uploads/2016/12/@MarkFRanklin_Nordress-v1.pdf〉.
[24] H.J. Henriksen, S. Stisen, X. He, M.B. Wiese, DK model based hydrological early warning system, Geol. Surv. Den. Greenl. Bull. 33 (2015).
[25] X. He, S. Stisen, W.M. Wiese, H.J. Henriksen, Designing a hydrological real-time system for surface water and groundwater in Denmark with engagement of stakeholders, Water Resour. Res. 30 (2016) 1785–1802, http://dx.doi.org/10.1007/s11269-016-1251-8.
[26] A. Ako, G. Eyong, G. Nkeng, Water resources management and integrated water resources management (IWRM) in Cameroon, Water Resour. Manag. 24 (5) (2010) 871–888.
[27] A. Almoradie, A. Jonoski, F. Stoica, D. Solomatine, I. Popescu, Web-based flood information system: case study of Somesul-Mare, Romania, J. Environ. Eng. Manag. 12 (5) (2013) 1065–1070.
[28] A. Almoradie, I. Popescu, A. Jonoski, D. Solomatine, Web-based access to water related data using OGC WaterML 2.0 (SI), Int. J. Adv. Comput. Sci. Appli. 7 (2013) 83–89, http://dx.doi.org/10.14569/SpecialIssue.2013.030310 (Special Issue on “Building a Regional Observation System in the Black Sea Catchment).
[29] A. Almoradie, V.J. Cortes, A. Jonoski, Web-based stakeholder collaboration in flood risk management, J. flood risk Manag. 8 (2015) 19–38.
[30] A. Almoradie, Networked Environments for Stakeholder Participation in Water Resources and Flood Management (Doctoral Thesis/Disertation), Master of Science in Hydroinformatics, UNESCO-IHE Institute for Water Education, Delft, the Netherlands, 2014.
[31] T. Webler, H. Kastenholz, O. Renn, Public participation in impact assessment: a social learning perspective, Environ. Impact Assess. Rev. 15 (5) (1995) 443–463.
[32] M.B. Abbott, A. Jonoski, The democratisation of decision-making process in the water sector II, J. Hydroinformatics 3 (1) (2001) 35–47.
[33] UN-ESCAP. Guidelines on participatory planning and management for flood mitigation and preparedness. Water Resources Series No. 82. New York. United Nations, 2003.
[34] I. White, R. Kingston, A. Barker, Participatory geographic information systems and public engagement within flood risk management, J. Flood Risk Manag. 3 (4) (2010) 337–346.
[35] A. Jonoski, L. Alfonso, A. Almoradie, I. Popescu, S. van Andel, Z. Vojinovic, Mobile phone applications in the water domain, Environ. Eng. Manag. J. 11 (5) (2012).
[36] J. Krykow, A Methodological Framework for Participatory Processes in Water Resources Management (Ph.D. Thesis), Twente University, 2009.
[37] O. Renn, Risk governance, Coping with Uncertainty in a Complex World, Earthscan, 2008, p. 445.
[38] S.A. Wheeler, D.H. MacDonald, P. Boxall, Water policy debate in Australia: understanding the tenets of stakeholders' social trust, Land Use Policy 63 (2017) 246–254.
[39] A. Harjanne, E. Pagneux, L.F. Jørgensen, A. Perrels, P. van der Keur, F. Nadim, J.K. Rød, E. Raats Resilience to natural hazards: An overview of institutional arrangements and practices in the Nordic countries. NORDRESS WP6.1 report 3.6. Available from 〈www.nordress.hi.is〉.
[40] (a) Lonkila. Aspects of strategic climate work in Nordic municipalities NordLead Project Final Report. TemaNord 2012: 557.
(b) Y.Q. Liu, A.H. Weerts, M. Clark, H.J. Hendricks Franssen, S. Kumar, H. Moradkhani, D.J. Seo, D. Schwanenberg, P. Smith, A.I.J.M. van Dijk, N. ., van Velzen, M. He, H. Lee, S.J. Noh, O. Rakovec, P. Restrepo, Advancing data assimilation in operational hydrologic forecasting: progresses, challenges, and emerging opportunities, Hydrol. Earth Syst. Sci. 16 (2013), http://dx.doi.org/10.5194/hess-16-3863-2012
[41] UN/ISDR. Global Survey of Early Warning Systems: United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UN/ISDR) International Environment House II, 7-9 Chemin de Balexert, CH 1219 Chatelaine, Geneva 10, Switzerland. isdr@un.org. 〈www.unisdr.org〉.
[42] L. Alfonso, J. Chacon, G. Pena-Castellanos, Allowing Citizens to Effortlessly Become RainfallSensors, in 36th IAHR World Congress edited.The Hague, The Netherlands, 2015.
[43] J. Cortes-Arevalo, J. Chacon, L. Alfonso, T. Bogaard, Evaluating data quality collected by using a video rating scale to estimate and report rainfall intensity, in 36th IAHR World Congress edited.The Hague, The Netherlands, 2015.
[44] T. Jacobsen DHI erfaringer med realtids- og varslingssystemer – den korte version. in: Proceedings of the GEUS workshop. Realtidsvarsling. 7. Oktober (Slide presentation in Danish).
[45] C. Jex New model can help predict flooding two days in advance. 〈http://sciencenordic.com/new-model-can-help-predict-flooding-two-days-advance〉.
[46] Luonnononnettomuuksien varoitusjärjestelmä LUOVA (in Finish): 〈https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/78637/Julkaisuja_29_2005.pdf?Sequence=1〉.
[47] A. Harjanne, T. Ervasti, Analysis of user trends and behavior in online and mobile weather and climate services. FMI Report:10. Available online: 〈https://helda.helsinki.fi/handle/10138/144242〉, 2014.
[48] A. Harjanne, T. Ervasti, J.A. Karhu, H. Tuomenvirta, Combining science education with citizen science – experiences from a research institute-led science education project, LUMAT 3 (7) (2015) 948–959.
[49] F. Nadim Acceptable risk for facilities subjected to geohazards. NGI. NORDRESS workshop on risk assessment and acceptable risk. 〈http://nordress.hi.is/wp-content/uploads/2016/12/2016.12.01-NORDRESS-Workshop-on-Acceptable-Risk_Nadim.pdf〉.
[50] J. Mysiak, H.J. Henriksen, C. Sullivan, J. Bromley, C. Pahl-Wostl, The Adaptive Water Resource Management Handbook. Earthscan, 2010.
[51] C. Pahl-Wostl, Requirements for adaptive water management, in: C. Pahl-Wostl, P. Kavat, J. Möltgen (Eds.), Adaptive and Integrated Water Management. Coping with Complexity and uncertainty. Springer Verlag, Heidelberg, 2007, pp. 1–22.
[52] B. Walker, C.S. Holling, S.R. Carpenter, Kinzig A. Resilience, adaptability and transformability in social-ecological systems, Ecol. Soc. 9 (2) (2004) 5.
[53] U. Wehn, M. Rusca, J. Evers, V. Lanfranchi, Participation in flood risk management and the potential of CO: A governance analysis. ICFM6. Sao Paulo, Brazil, Sept 2014.
[54] U. Wehn, J. Evers, The social innovation potential of ICT-enabled citizen observatories to increase eParticipation in local flood riskmanagement, Technol. Soc. 42 (2015) 187–198.
[55] Lanfranchi, V., Wrigley, S.N., Ireson, N. and Wehn, U. Citizens' Observatories for Situation Awareness in Flooding. In: Proceedings of the 11th International ISCRAM Conference – University Park, 2015. Pennsylvania, USA, May 2014. S.R. Hiltz, M.S. Pfaff, L. Plotnick, and P.C. Shih, eds.
[56] E. Bøgh Landsdækkende data-dreven hydrologisk modellering, visualisering og udtræk af sammenhængende data om det hydrologiske kredsløb til understøttelse af langsigtet planlægning, klimatilpasning og risikohåndtering i realtid. Notat med henblik på redegørelse af udviklingsområde. Styrelsen for dataforsyning og effektivisering. 19. Januar. 15 pp. (In Danish, see: 〈http://sdfe.dk/data-skaber-vaerdi/faelles-data-om-terraen-klima-og-vand/〉).
[57] O. Rakovec, A.H. Weerts, P. Hazenberg, P.J.J.F. Torfs, R. Uijlenhoet, State updating of a distributed hydrological model with Ensemble Kalman Filtering: effects of updating frequency and observation network density on forecast accuracy, Hydrol. Earth Syst. Sci. 16 (9) (2012) 3435–3449.
[58] M.P. Clark, D.E. Rupp, R.A. Woods, X. Zheng, R.P. Ibbit, A.G. Slater, J. Schmidt, M.L. Uddstrom, Hydrological data assimilation with the ensemble Kalman filter: use of streamflow observation to update states in a distributed hydrological model, Adv. Water Resour. 31 (2008) 1309–1324.
[59] K. Daniel, O. Barrateau, Water governance across competing scales: coupling land and water management, J. Hydrol. 519 (2014) 2367–2380.
[60] Lonkila (Ed).Aspects of strategic climate work in Nordic municipalities NordLead Project Final Report, Editor Kirsi-Marja Lonkila,(Union of the Baltic Cities –Commission on Environment). ISBN 978-92-893-2443-4http://dx.doi.org/10.6027/2012-557.
[61] M. Mazzoleni, V.J. Cortes Arevalo, U. Wehn, L. Alfonso, D. Norbiato, M. Monego, M. Ferri, D.P. Solomatine, 'Exploring the influence of citizen involvement on the assimilation of crowdsourced observations: a modelling study based on the 2013 flood event in the Bacchiglione catchment (Italy)', Hydrol. Earth Syst. Sci. 22 (2018) 391–416.